Superheterodyne Amplification of Electromagnetic Waves of Optical and Terahertz Bands in Gallium Nitride Films

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Abstract—Superheterodyne amplification of electromagnetic waves of optical and terahertz bands in the case of three-wave interaction in n-GaN films with the space change wave of millimeter band amplified due to negative differential resistance is studied. It is shown that amplification of the space change wave in n-GaN films may be achieved on higher frequencies \( f \leq 500 \text{ GHz} \) than when using GaAs. The case of three-wave resonant interaction of two counter-propagating waves with the space charge wave is considered for the waveguide on based on GaN film on dielectric substrate. It is shown that gain of electromagnetic waves of optical band may reach 20–40 dB on the waveguide lengths of up to 100 \( \mu \text{m} \).

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1. INTRODUCTION

Radiation in the transition band from millimeter to optical waves, the so-called terahertz band \( f = 0.1–30 \text{ THz} \), is widely used today in various spheres of science, medicine and technology: in spectroscopy, diagnostics and cure of various diseases, scanning in airports, study of atmosphere phenomena, etc. [1–7]. At the present time both electron-beam (gyrotron, backward-wave tubes) and laser (infrared lasers, cascade quantum lasers, lasers on free electrons) devices serve as sources of terahertz radiation. Except for some of them that belong to infrared band, the majority of them are bulk structures: vacuum lamps and light cascading devices. Such devices are difficult to combine with classic millimeter band devices, the majority of which use traditional microwave component base of modulators, phase shifters, delay lines, etc. It is worth searching for non-traditional ways that allow using the already common element base compatible with traditional microwave devices. Such a way may consist in the suggested below method of superheterodyne amplification of electromagnetic (EM) waves during three-wave interaction in films made of traditional (gallium arsenide GaAs) and new (nitrides GaN, InN) materials. This method is based on transferring of the space change wave (SCW) gain to the high-frequency EM wave during three-wave resonant interaction. SCW gain is caused by negative differential conductivity.

Amplification of microwave SCW in n-GaAs films due to negative differential conductivity has been studied since long time ago [8, 9]. Transfer of SCW gain to EM waves of terahertz and infrared bands during three-wave interaction, the so-called superheterodyne amplification [11], has been studied as well [10]. However the frequency band of amplified EM in GaAs films has an upper boundary due to the following reasons. Negative differential conductivity (NDC) in GaAs takes place in the case of relatively low levels of alloying, and, consequently, equilibrium electron concentrations of \( n_0 \leq 3 \times 10^{16} \text{ cm}^{-3} \) [12, 13], so the frequency band has an upper boundary of \( f \leq 50 \text{ GHz} \). Besides, since modulation amplitude of electron concentration of SCW is limited by the value \( n_0 \), modulation of dielectric permeability of EM waves appears to be small as well.

Effectiveness of superheterodyne amplification may be increased by using new semiconductor materials like gallium nitride GaN and indium nitride InN [12–16]. These materials possess the following properties: critical fields for observing NDC are high (\( E_{\text{cr}} \sim 100 \text{ kV/cm} \)), the corresponding frequency band is wider (\( f \leq \)